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A Status Report on the Energy Efficient Engine Project

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**A STATUS REPORT ON THE ENERGY
EFFICIENT ENGINE PROJECT**

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SUMMARY

The Energy Efficient Engine (E³) Project is directed at providing, by 1984; the advanced technologies which could be used for a new generation of fuel conservative turbofan engines. The project is conducted by NASA through contracts with the General Electric Company and Pratt & Whitney Aircraft. This paper summarizes the scope of the entire project and the current status of these efforts. Included is a description of the preliminary designs of the fully developed engines, the potential benefits of these advanced engines, and highlights of some of the component technology efforts conducted to date.

THE VIABILITY OF AIR TRANSPORTATION is threatened by fuel prices that have been rising at a rate greater than the rate of inflation (1)*. In 1973, at the time of the OPEC oil embargo, fuel cost was 25 percent of aircraft direct operating cost (DOC). Fuel cost currently accounts for nearly 60 percent of DOC (2). Improvements in the efficiency of air transport fuel utilization is of primary importance in minimizing the burden of fuel cost, and its effect on DOC, on the world's airlines.

The National Aeronautics and Space Administration (NASA) has implemented the Aircraft Energy Efficiency (ACEE) Program which addresses improving fuel efficiency from the standpoint of fuel conservation and aircraft operating economics. One of the major elements of the ACEE program is the Energy Efficient Engine (E³) Project. While this project is focused on reduced fuel consumption, future engines must also be economically attractive to airlines and environmentally acceptable to society. Therefore, a balanced set of goals for fully-developed and flight-qualified engines was established at the onset of the project to guide the design and technology efforts. These goals are to be assessed relative to current turbofan engines (specifically, the CF6-50C for GE and the JT9D-7A for PWA) and are as follows:

- o Reduce fuel usage
 - at least 12 percent reduction in specific fuel consumption (SFC)
 - at least 50 percent reduction in performance deterioration rate
- o Improve operating costs
 - at least 5 percent reduction in direct operating cost (DOC)
- o Meet future environmental regulations
 - FAA's 1978 noise regulations:
FAR-36 (1978)
 - EPA's 1981 emissions standards

NASA has contracted, in parallel, with the two domestic manufacturers of large turbofan engines for accomplishment of the E³ Project (The General Electric Company (GE) Aircraft Engine Group and the Pratt & Whitney Aircraft Group (PWA) of United Technologies Corporation). Building on their experience and the NASA research and technology base, these two companies have selected engine thermodynamic cycles and have completed preliminary designs of engine configurations projected to meet the project goals. Both manufacturers are cur-

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rently in the component development phase of the project. The primary stages of the project are shown in Figure 1, a summary of the [3] schedule.

The basic engine design, as it could be configured for future commercial application, is called the Flight Propulsion System (FPS). The first element of the project pertains to generating the FPS designs which serve as the basis for defining the technology advances to be evaluated in the subsequent phases. The FPS designs are also used in the prediction of performance benefits that such designs would offer when fully developed to a flight-certified engine. A low-level of effort will continue throughout the duration of the project to update the FPS designs and projections of expected benefits. Such updates will be based upon results of the component and systems technology development.

The second project element, component technologies, pertains to detailed design of each component and associated technology development efforts to aid in the selection and confirmation of advanced design concepts. Subsequently, full-scale versions of most of the components will be fabricated and tested in rig tests to demonstrate the performance levels predicted for each advanced component design.

The third major project element involves integration of the advanced component designs into engine systems. The purpose of this element is to experimentally assess the integrated performance of the components and the various advanced systems-technology features that can be evaluated only in systems tests. In the case of GE, the high-spool components (i.e., - the high-pressure compressor and turbine plus the combustor) will first be tested as a core-engine system. Both contractors will evaluate the high-spool components integrated with the low-spool components (i.e., - the fan, the low-pressure compressor and turbine, and the mixer and simulated nacelle) in total engine systems tests that have been termed "Integrated Core/Low-Spool" (ICLS) tests. These engine system tests are considered to be the primary means of demonstrating technology-readiness and, while the performance of a fully developed engine will not be attained, the tests provide the basis for the final update of the FPS design.

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Candidate engine configurations and cycle conditions were selected by each engine manufacturer during preliminary engine definition studies (3). Inputs to these studies in the

areas of airplane/mission definition and engine/airframe integration were made by Boeing, Douglas, and Lockheed, as sub-contractors to GE and PWA (4, 5). Preliminary engine designs have since been developed by GE and PWA that are projected to meet or exceed E³ goals. The resulting thermodynamic cycles chosen by GE and PWA, compared to current high-bypass (reference) engines, are presented in Figure 2. Artist's conceptions of each of the initial E³ configurations (FPS designs) are shown in Figures 3 and 4. Both engines employ two spools, have a total inlet airflow of about 635Kg per second (1400 pounds per second) with a core airflow of about 52Kg per second (115 pounds per second), and have long-duct nacelles with exhaust mixers. Both designs are sized to produce about 160,000 Newtons (36,000 pounds) of takeoff thrust, a level scalable to other sizes for commercial transport applications. E³ technology developments can also be scaled so that they can be applied to derivative versions of current engines at other thrust levels.

The improvements in SFC realized by the E³ designs are expected to be at least 14 percent. Contributions to these improvements are depicted in Figure 5. (Note that these SFC improvements are relative to the respective manufacturer's baseline, or reference engine, and thus are not directly comparable on an absolute basis.) The major portion of the SFC reduction results from improvements in the performance of the major engine components. Accordingly, principal emphasis is directed at developing components that incorporate aggressive advances in technology (6). While the overall engine configurations and cycles for both manufacturers energy efficient engines are similar, each manufacturer is developing unique component designs incorporating different technologies.

This paper will present a summary of the preliminary designs of the fully developed engines (or FPS) and potential benefits of these engines. Also presented is a description of the results of current activity in E³ high-pressure compressor testing, exhaust mixer model testing, combustor rig (both full annular and sector) tests, high-pressure turbine airfoil fabrication development, and model powered nacelle tests, thus summarizing the status of the E³ Project.

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PRELIMINARY FLIGHT PROPULSION SYSTEM DESIGNS

E³ FPS designs have been completed by GE and PWA during the first two years of project effort. These FPS designs include the total aircraft engine systems: bare engine components, plus nacelle, exhaust-gas mixer, engine control system, and engine accessories. The designs are based on the results of the earlier engine definition studies and represent each manufacturers current views on the nature of their next generation of turbofan engines. These FPS designs were used to define the component and system technology advances that are required during the project duration. Also, the FPS designs are used to predict the performance benefits that such advanced engines would offer when fully developed to flight-certified status.

The major effort on the FPS designs has been completed (7, 8, 9, 10). A low-level of effort will continue throughout the project duration to permit up-dating of the designs based on results of the component development and systems technology elements of the project. The performance predictions of the up-dated final FPS designs at the conclusion of the project will thus serve as the basis for comparison to the project design goals.

A summarized description of both the GE and PWA FPS designs follows:

GENERAL ELECTRIC CONFIGURATION - The GE design shown in Figure 6 has two co-rotating spools and employs only two main frames. The base engine length is about 10 percent shorter than a CF6-50 reference engine scaled to equivalent thrust level. The nacelle is a slender (fineness ratio of 2.5), low drag design. Mounting the accessory package inside the core cowl allows for a low nacelle frontal area. The ratio of the inlet highlight diameter to the maximum nacelle diameter is 0.86. Bulk absorber type acoustic treatment is used in the inlet, inner and outer walls of the fan duct, and aft of the low pressure turbine at the end of the core flow passage. The nacelle includes a fan-stream thrust reverser totally encased in the outer structure with no actuation links in the by-pass stream.

The fan is a single stage, low tip-speed design incorporating a composite frame. The solid titanium blades incorporate a single damper located at approximately 55 percent span and near the trailing edge to minimize aerodynamic losses. The vanes are integrated with the support struts to minimize the number of airfoils, thereby reducing fan frame weight and cost.

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The integral vane-frame design requires that the vane/struts be large enough to provide adequate support but few enough in number to avoid excessive blockage. This results in about an equal number of blades and vanes. To offset the increased noise associated with a vane-blade ratio near unity, the axial spacing between blades and vanes has been increased, as compared to current engines, to approximately two chord widths. Tests have shown that this approach results in fan generated noise levels as low as conventional designs. The inlet is cantilevered from the fan-frame and is independent of the fan casing. Therefore, the fan casing is not subject to any flight loads and the fan can be operated with tighter clearances than existing designs. This feature also helps performance retention by minimizing blade tip rubbing. A quarter-stage island booster is incorporated in the fan duct which provides automatic core flow matching without variable geometry and also acts as a foreign object separator, centrifuging dirt and other particles radially outward and back into the bypass stream away from the engine core.

The compressor is an aggressive design aimed at achieving a pressure ratio of 23:1 in only ten stages by utilizing low aspect ratio, rugged airfoils. It has four variable-vane stages and a variable inlet guide vane. Active clearance control (ACC) is employed on the last five stages to achieve tight running clearances. In operation, cooler front stage bleed air is allowed to pass over the outer surface of the aft inner casing. Running clearances between the blades and vanes are varied by controlling the cooling air flow with a modulating valve. In this manner, clearances are minimized, thereby improving performance during climb and especially at cruise. During periods of potential high engine deflection, the casing is uncooled and therefore expands to increase the clearance. This capability to increase clearances minimizes performance deterioration due to inadvertent tip rubs which might normally occur during periods of high aerodynamic and maneuver loads.

The combustor is a double-annular design for low emissions and is an outgrowth of the NASA Experimental Clean Combustor Program. A segmented, or "shingled", liner is utilized to provide increased life and low maintenance. The split duct diffuser divides the flow for the two concentric burning zones, thus permitting a very short combustor length.

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The high pressure turbine is a high efficiency two-stage design. Both stages incorporate high tip-speeds with only modest increases in turbine temperatures over current engines. Active clearance control is also incorporated in the design. Controlled amounts of fan air are allowed to impinge on the turbine case, thus reducing the clearances.

This two-stage turbine is cooled by means of compressor-discharge and interstage air for the vanes and blades, respectively. A major design feature is the substantially extended life obtained through use of advanced directionally-solidified airfoil material, a ceramic shroud over the first stage rotor, advanced powder metallurgy disks, and through elimination of bolt-holes in the disks. High-pressure cooling air requirements have also been reduced through the use of the advanced turbine materials.

The low pressure turbine has five uncooled highly efficient stages and is acoustically tuned to reduce noise. The high efficiency will be achieved by reducing pressure losses, by improving the aerodynamic design, and by use of active clearance control. A short transition duct between the turbines permits high blade velocities in the initial stages, with lower overall average blade loading.

The GE/E³ design is a long duct, mixed flow configuration. The hot core stream is mixed with the cooler bypass stream through an advanced lobe shaped mixer before expansion through a mixed flow exhaust nozzle. The 12 lobed mixer and the mixing chamber are short in length to minimize weight, internal pressure losses, and external nacelle drag.

A comparison of the GE/E³ cycle with the cycle of the CF6-50C reference engine is shown in Figure 2. As described earlier, the E³ design has a mixed flow exhaust and has a much higher bypass ratio than the reference engine. The E³ fan pressure ratio is slightly lower and the compressor pressure ratio is almost double that of the CF6-50C. The E³ FPS design has a 36:1 overall pressure ratio, a turbine temperature increase, and is sized for 160,000 Newtons (36,000 pound) takeoff thrust. The specific fuel consumption (SFC) of the E³ is projected to be 14.2 percent lower than the reference engine at the maximum cruise operating condition.

Figure 7 shows a comparison of the GE/E³ FPS predicted performance relative to the project goals. ~ a 14.2 percent reduction in

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SFC surpasses the 12 percent goal with margin. A DOC reduction ranging from 5 percent to 12 percent would thus accrue. (DOC calculations were made for four different advanced aircraft by the three major domestic airframe companies (4). The price of fuel used for these calculations was \$.10/liter (\$.40/gal.) domestic and \$.12/liter (\$.45/gal.) international. These DOC numbers are currently being updated using current and expected future fuel prices, and the levels of DOC improvement for the E³ are expected to increase significantly with the higher fuel prices.) Performance retention features have been designed into the E³ through the basic design features, such as the extensive use of active clearance control. The E³ FPS is projected to be at least 3 EPNdB quieter than the goal level for all measuring conditions (takeoff, sideline, and approach) for all four advanced aircraft studied. Emissions goals are still expected to be met for the FPS design, with optimization of cooling/dilution air flows and other technology features, and with full development of the combustor.

PRATT & WHITNEY CONFIGURATION - The PWA/E³ design is shown in Figure 8. The engine is a two-spool high-bypass turbofan with mixed core and fan exhaust. The two major frames and both main shaft bearing compartments are situated between the compressors and between the turbines to independently support the counterrotating rotors. The nacelle features extensive use of acoustic treatment throughout the inlet and exhaust ducts and is designed to share flight loads through the load-carrying fan ducts which transmit much of the inlet gust load and other cowl loads around the engine case and to the engine mounts.

The E³ fan features a shroudless, hollow titanium blade design to provide efficiency improvement without an offsetting weight increase. The spacing between the fan blades and exit guide vanes was increased to provide a low noise configuration. The four-stage low-pressure compressor and ten-stage high-pressure compressor utilize controlled diffusion airfoils and low-loss endwall concepts to raise compressor efficiency levels. Such concepts include rotor tip trenches and reduced tip clearances as well as minimized cavity volumes.

The staged combustor has two in-line combustion zones to control emissions. A segmented-liner configuration has been incorporated to increase combustor liner life as well as reduce cooling air requirements.

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The overall length of the combustor has been reduced by the use of a short, low-loss, dump-type diffuser section.

To obtain a large reduction in number of airfoils, initial cost, and engine maintenance costs, a single-stage, high-work, high pressure turbine has been incorporated. Single-crystal alloy airfoils are used to reduce cooling air-flow requirements. Ceramic outer air seals are also incorporated to reduce cooling air requirements as well as permitting the use of tighter rotor tip clearances, hence lowering rotor tip losses. The four-stage low-pressure turbine utilizing low-loss airfoils requires no airfoil cooling and counter-rotates relative to the high spool, thus permitting lightly-loaded low-pressure turbine inlet vanes for increased turbine efficiency. The 18-lobe scalloped, high penetration, exhaust mixer is designed to provide high mixing efficiency with a relatively short mixer and mixing chamber. The short length serves to minimize pressure loss, weight, and external nacelle drag.

Active clearance control on the rear section of the high-pressure compressor and on the turbines is designed to closely match rotor and case diameters (minimize rotor tip clearances) during cruise operation without inducing rubs during takeoff and climb maneuvers (requiring increased rotor tip clearances). This is achieved through proper selection of rotor and case materials, external fan air impingement tubes on the high-pressure compressor, and an internal case air-cooling system on the turbines.

Cycle parameters for the PWA/E³ FPS design are compared to those of the JT9D-7A reference engine in Figure 2. Comparison is at maximum cruise flight conditions. The E³ cycle exhibits a somewhat higher bypass ratio and fan pressure ratio relative to the reference engine, and has a significantly higher compressor pressure ratio and overall pressure ratio. E³ turbine temperatures are seen to be about 93K (200 F°) hotter than in the reference engine. The engine is currently sized for about 160,000 Newtons (36,000 pounds) takeoff thrust.

Figure 9 is a comparison of currently predicted performance for the PWA E³/FPS relative to the program goals. Projected cruise SFC indicates a 15.1 percent improvement over the JT9D-7A reference engine as compared to the 12 percent program goal. DOC projections were calculated for seven study aircraft based on common economic ground rules (10). The range of DOC reduction for the study aircraft utilized is

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currently projected to be from 5 to 10 percent which meets or exceeds the goal of 5 percent. (Fuel prices of \$.10/liter (\$.40/gal.) for the domestic aircraft and \$.12/liter (\$.45/gal.) for the intercontinental aircraft were used for these projections.) Many performance retention features have been incorporated into the E³ design to reduce projected in-service SFC deterioration to the goal level (50 percent of reference engine experience). These features include the load sharing nacelle, the short, stiff rotor configuration, active clearance control, and the use of abradable rub strips over the blade tips. Noise calculations for the fully-treated, mixed exhaust nacelle indicate the potential of meeting (with 2 EPNdB margin) the FAR 36 (1978) noise rules in future domestic and international aircraft. Estimates of EPA emission parameters for the FPS design fall below the proposed 1981 new engine standards for carbon monoxide and unburned hydrocarbon levels and thus are projected to meet the program goals. But, despite the use of staged combustion, NO_x estimates exceed the proposed 1981 regulations by over 50 percent. The E³ combustor development program now in progress, however, shows the promise of further reducing NO_x emissions toward the goal levels.

STATUS OF COMPONENT DEVELOPMENT

Since the major contribution to SFC improvement of the E³ designs will be achieved through performance improvements in each of the major engine components, the primary emphasis is on the development of component technologies. Full-scale versions of most of the components will be fabricated and rig tested to demonstrate predicted performance levels. Following the component development effort, the successfully-tested components will be integrated into the core and ICLS systems to experimentally assess the integrated performance of the components and the advanced system technology features.

As shown in Figure 1, the component technologies effort was initiated early in the project and continues for a period of approximately four years. This effort leads to engine system (ICLS) tests in the mid to late 1982 time frame for GE and PWA, respectively.

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Project efforts are currently concentrated on the development of component technologies. Some supporting technology efforts have been completed and others are currently underway. Some full-scale component tests have been

initiated but the majority of the effort will be conducted in 1981. A summary of the significant results to date follows:

GENERAL ELECTRIC - Highlights of some of the component technology efforts conducted to date are:

1-6 Stage High-Pressure Compressor Test -

A full-scale rig test of the first six stages of the 10-stage E³ high pressure compressor was tested early in 1980.

The test configuration is shown by the shaded stages in Figure 10. Blading, flowpath, clearances, and inlet flow field were identical to that required for the FPS at cruise. A special outer casing, however, was utilized to allow six variable vane stages rather than the first four stages as in the flight design. The additional two variable stator stages permit greater flexibility in matching the compressor in the starting region and will assist in generating data required for matching the aft fixed stages to the flow generated by the front stages. This test is the first in a series of three tests planned for the compressor prior to incorporation into the core and ICLS systems. A photograph of the six stage test rotor while installed in the balance machine is shown in Figure 11.

The primary test goals for the 1-6 stage vehicle were to achieve an operating pressure ratio of 9.83 at design weight flow and an adiabatic efficiency of 84.1 percent. This point is shown in Figure 12, as well as the predicted stall line and assumed efficiency goals. Initial testing with the original stator schedule indicated good efficiency and low-speed stall margin, but there was less than desired stall margin near the design point. The inlet guide vane and stator 1 were then scheduled a few degrees closed to improve high-speed performance.

Several stator setting schedules were tested, and a preliminary performance map for the optimized stator schedule is shown in Figure 12. To meet the design pressure ratio and weight flow, the compressor required over-speed operation. At the over-speed condition, the efficiency slightly exceeds the test goal value, but the high speed stall margin was still somewhat lower than desired. These results and the low-speed performance are very encouraging, and further testing in the ten-stage configuration will be performed to meet the high-speed stall margin requirements.

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Radial survey data measuring flow angle, total pressure, and total temperature were recorded. Measurements established that low velocity and low stage hub pressure rise were encountered at high speeds. Modifications have been made to the blading to improve the hub pressure rise for the first 1-10 compressor test.

The mechanical performance of the compressor closely matched that predicted. The measured blade frequencies and shaft critical speeds occurred where predicted and were of the expected mode and amplitude. Neither blade vibration nor shaft motion limited the flow range or speed, and there was no blade flutter observed within the operating range of the compressor.

In general, the performance of the 1-6 compressor was considered promising, both mechanically and aerodynamically. The achievement of the efficiency goals, even with the blade hubs down in work input, is very encouraging. Although the real potential of the GE HPC won't be known until after the 1-10 testing, streamline computations show that the blade modifications on the front stators and rear rotors should meet or exceed the design intent for the 1-10 test.

Combustor Development - The GE design for the E³ combustion system is shown in Figure 13. The double-annular design was chosen for its low emissions potential and is based on the technology improvements achieved in the NASA-GE Experimental Clean Combustor Program (11) AND THE NASA-GE Quiet Clean Short Haul Experimental Engine Program (12). These cooperative programs developed emissions reduction technology that will help aircraft engines satisfy the proposed 1981 EPA aircraft emissions standards (13). These earlier two-zone combustors were relatively large, however. The E³ design is considerably shorter in overall length, and the combustion zone has been reduced to .17 meters (7 inches). The desire to reduce DOC (by minimizing maintenance costs) has led to a liner design with considerably longer life. The E³ liner consists of segments or "shingles" which are free-riding relative to each other. This feature alleviates the life limiting hoop-stresses which normally build up in conventional continuous ring liner designs when subjected to the rapid heating and cooling cycles encountered in normal combustor operation. The shingle liner concept is shown in Figure 14.

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The GE combustor development effort consists of tests with a 60° sector rig and a full-scale annular test rig. The sector rig effort will be directed primarily at obtaining low emission levels in the pilot stage at idle conditions. Modifications in combustor design will be evaluated to determine effects of dome geometry and swirl cup design and spacing. Full-annular rig tests will be conducted for the basic E³ combustor design. As design features are identified from sector and full-annular tests, modifications will be made to improve and simultaneously meet emissions, exit temperature profiles, light-off, and other performance requirements. Sector and full-annular development tests will be conducted with machined ring type liners to facilitate design modifications. Upon selection of the final combustor design, full-annular tests will be conducted to verify performance and emissions characteristics of the combustor with a shingle liner, prior to engine installation.

Sector and full-annular rig tests are currently underway. Exhaust emission levels of carbon monoxide (CO), total unburned hydrocarbons (HC), and oxides of nitrogen (NO_x) were measured during these tests. Emission levels for the sector tests in terms of EPA parameters (EPAP) are shown below.

	<u>SECTOR TESTS</u>	<u>E³ GOAL</u>
CO	3.0	3.0
HC	.32	.4
NO _x	3.71	3.0

Emissions results obtained to date are encouraging. However, continued development will be required as combustor design modifications and tradeoffs are made to meet temperature profile and ignition requirements.

Combustor exit temperatures were also measured in the tests of sector and full-annular hardware. Pattern factor, which is defined as:

$$P_F = \frac{T_4 \text{ max} - T_4 \text{ ave}}{T_4 \text{ ave} - T_3}$$

Where:

T₄ max = the maximum exit temperature
T₄ ave = the average exit temperature
T₃ = combustor inlet temperature

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is a representation of the maximum measured circumferential temperature deviation from the

average measured temperature. Profile factor, which is defined as:

$$Pr_F = \frac{T_{4 \text{ imm ave (max)}} - T_{4 \text{ ave}}}{T_{4 \text{ ave}} - T_3}$$

where $T_{4 \text{ imm ave (max)}}$ is the maximum value of the circumferential average exit temperatures at the various radial immersions, represents the maximum measured average radial temperature deviation from the average measured temperature. The goal value for pattern factor is .25. The profile factor goal is shown in Figure 15. Also shown in the figure are the profile factor test data for the full-annular combustor. The measured pattern factors were .50, .41, and .25 for the pilot/total fuel splits of .30, .40, and .50 respectively. Profile factor and pattern factor are seen to be very sensitive to fuel split. At an off-design pilot/total fuel split of .5, both profile factor and pattern factors are near goal. Temperature profile tailoring characteristics are expected to be improved by tailoring the wall cooling/dilution airflows.

Mixer Development - General Electric has selected a mixed flow design for their Energy Efficient Engine (E3). The benefits from a mixed flow design can be as high as 3-4 percent in reduced specific fuel consumption (SFC) relative to a separate flow design. To obtain these large benefits, the mixed flow system must achieve high levels of mixing while minimizing the accompanying pressure losses. Minimizing the pressure losses is as important as achieving high mixing because an increase in pressure loss will usually result in an almost equal increase in SFC (i.e., one percent increase in pressure loss will yield about one percent increase in SFC). The exhaust system components (mixer, centerbody, and long duct nacelle) must also be designed to minimize weight and nacelle drag. As with high pressure losses, the added weight of a mixed flow system and/or the drag of the long duct nacelle can offset all the gains from the mixing. The overall objective, therefore, is to generate a mixed flow system design which effectively mixes the core and fan flows in a relatively short length, keeps any pressure losses to a minimum, and is relatively light weight.

Current mixer design methodology is primarily empirical. Analytical codes for evaluating the complex flow fields of a mixed

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flow system are not available for high bypass ratio systems. Therefore, the GE mixer development program is based on a series of scale model tests. To date, approximately 31 different mixer/centerbody/outer shroud combinations have been tested. Some of the test results have been reported previously (15). The primary geometric test variables are shown in Figure 16. The geometric variations were made primarily on mixer designs with the two lobe shapes shown. Variations in lobe number, lobe perimeter, lobe penetration, and scalloping (curved cutout of mixer sidewall) were all examined on lobe shape 'A'. Variations in mixing chamber length, lobe penetration, and scalloping were examined on lobe shape 'B'. Lobe shape 'B' also had a much smaller mixer to centerbody gap.

Lobe number and lobe perimeter were not found to have a significant effect on overall performance. Some variations in the level of mixing and the amount of pressure loss were observed, but the net changes in terms of SFC were small. This was the case for lobe shape 'A', but the trends may be different for other lobe shapes.

Lobe penetration, mixing chamber length, and scalloping were all found to have more significant effects on mixer performance. Some test results from variations in these parameters are shown in Figure 17. The results are shown in terms of SFC improvements relative to a long duct system with no mixing. An increase in lobe penetration is shown to significantly improve the performance of lobe shape 'B'. Increasing the penetration was found to increase the amount of mixing. The pressure losses also increased with increasing penetration, but the penalty from the increased pressure loss was less than the benefit from the mixing. An optimum value of penetration most likely exists where the difference between the benefits of increased mixing and the debits due to increased pressure loss is the largest. This optimum value is greater than the levels shown here and may be different for different lobe shapes. Variations in lobe penetration were also examined on lobe shape 'A'. However, this lobe design exhibited some separated flow near the end of the core lobes. As penetration increased, the size of the separation region also increased, with increased pressure losses. Even with the separated flow, the level of mixing continued to increase with increasing penetration. However, the increasing pressure losses offset the mixing gains, and the highest penetration

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mixers actually had lower overall performance. Lobe shape "B" did not exhibit this kind of flow separation and therefore had lower pressure losses, resulting in improved overall performance with increased penetration.

All of the testing done on lobe shape "A" was done with a short mixing chamber length $L/D = .48$. Lobe shape "B" was tested with three different mixing chamber lengths ($L/D = .48, .58, \text{ and } .75$). The effect of a longer chamber was significant as shown in Figure 17. Since the actual mixing of the two streams occurs in the mixing chamber, it is to be expected that making this region longer results in increased mixing. A limit does exist, however, beyond which no further benefit from added length will be realized. Increased weight and increased nacelle drag will then become large enough to offset the increases in performance from more mixing. Based on the results shown here, the length of the GE FPS design was increased .25 meters (10 in.) to permit a longer mixer chamber.

Scalloping was also shown to have a significant effect on mixer performance. Five of the mixer models were tested both with full side walls and with scalloped sidewalls. The results for two of these mixer designs (for lobe shape "A") are shown in Figure 17. Scalloping is shown to produce a significant improvement in mixer performance. This was true for all of the models tested. The level of mixing was increased by the scalloping in all cases with virtually no increase in pressure loss. The amount of performance improvement was not constant, as some mixer designs showed more improvement from scalloping than others, but the effect was always an improvement.

The goal for the GE/E³ mixer component is to produce a 3.1 percent SFC improvement relative to a long duct design with no mixing. The 3.1 percent SFC improvement results from a mixing effectiveness goal of 75 percent and a pressure loss goal of 0.2 percent. The results from the tests completed to date shown an SFC improvement of 2.2 percent. Based on these tests, the original pressure loss goal now appears to have been too aggressive, and a level of about 0.4 percent is more realistic. A mixing effectiveness level of 75 percent is considered achievable. These levels would produce an overall SFC improvement of approximately 2.8 percent. Further test efforts are planned, and additional improvements are expected from an improved lobe shape, increased

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lobe penetration, and alternate geometric designs.

Long Duct Nacelle Tests - The incorporation of a mixer on an engine requires a long duct nacelle. This presents a new set of challenges to the aircraft/engine designer. Experience has shown that long duct nacelles that have high installed drag levels, making them impractical compared to the performance of separate flow nacelles. To address this problem in E³, a cooperative test program (NASA-Lewis, NASA-Langley, and GE) was conducted to evaluate the installed drag of the GE/E³ nacelle. The E³ nacelle and several other current technology nacelles were tested at Langley under a supercritical wing on an Energy Efficient Transport (EET) half-span model. The nacelle test configurations and their various positions relative to the wing are shown in Figure 18. Two separate flow nacelles and one current technology long duct nacelle were tested in addition to the GE/E³ nacelle. The E³ nacelle is shown in two positions relative to the wing.

Figure 19 shows the results of the installed tests. As might be expected, the separate flow nacelles exhibited lower drags than the current technology, long duct nacelle. The E³ nacelle in the more aft position also had relatively high installed drag. However, in the more forward position, the E³ nacelle drag was quite low, indicating a significant reduction in interference drag. In this forward position, the E³ long duct nacelle drag is comparable to separate flow designs. The test results indicate that with careful tailoring of the wing/pylon/nacelle combination, the installed drag of a long duct nacelle can be comparable to a conventional separate flow nacelle.

PRATT AND WHITNEY - Highlights of some of the component technology efforts conducted to date are:

Combustor Development - The significant design features of the E³ Combustor configuration, as designed by Pratt and Whitney, are shown in Figure 20. The two-zone in-line combustor is required to meet the emission goal levels for CO, HC, and NO_x. The carburetor tube fuel injection for the main zone assists in reducing NO_x levels as well as reducing the smoke to below goal levels. The incorporation of a segmented combustor liner supported by a separate frame and with advanced cooling allows for a long-life combustor configuration.

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Figure 21 shows two views of the segmented combustor liner to be used as a part of the E3 combustor development program. The segments are cast from a turbine-type material and feature feather seal slots to minimize leakage.

The technology required for the combustor development program is being provided by two support efforts prior to full-scale, full-annular rig tests scheduled for 1981. The first, the Diffuser/Combustor Model Test Program, has been completed. The purpose of this test program was to experimentally determine and optimize the aerodynamic performance of the diffuser/combustor flowpath, utilizing a modularized, full-scale, full-annular combustor model made of plexiglas and wood. All the goals of this program (i.e., separation-free diffuser flowfield, overall pressure loss ($\Delta P/P_3$) of 5.5 percent, and diffuser pressure loss of 3.0 percent) were met and are reported in Reference 16. The second effort, the Combustor Sector Rig Test Program, is currently in progress. A typical test setup of the PWA/E3 Combustor Sector Rig is shown in Figure 22. The test program consists of 21 tests. The first 17 tests use a sheet-metal louvered linear combustor to facilitate development of internal combustor geometry with low emissions and smoke while also meeting the design goal requirements for pattern factor and the other aerodynamic performance parameters. A view of this sheet-metal louvered combustor configuration is shown in Figure 23. The last four tests of the Combustor Sector Rig Program will be with the advanced segmented linear at maximum EEE operating conditions (30 atmospheres). These final configurations will incorporate the optimized results obtained from the initial 17 tests.

The status of results with comparison to goals of the Combustor Sector Rig Program, after 12 of the planned 21 tests, is shown in Figure 24. The test results are very encouraging. The two-zone combustor, has been staged over the full range of EEE operating conditions as well as having been re-ignited at altitude conditions. Other encouraging results to date are the low pattern factor of 0.15, a smoke number less than one, and HC and CO emissions which are below the goal levels. Testing in the near future will emphasize further reduction in NO_x and improved radial temperature profile, while maintaining a low smoke number and pattern factor.

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Mixer Development - For the Energy Efficient Engine, Pratt and Whitney selected a mixed-flow configuration, which shows a potential SFC benefit of 3 to 4 percent relative to an optimized separate flow configuration. The requirements for an acceptable design (i.e., high mixing, relatively short length and light weight, and minimal pressure losses) and the availability of design data are similar for Pratt and Whitney and General Electric. Therefore, as with General Electric, the Pratt and Whitney mixer development program is based on a series of scale model tests. The first of two test series has been completed and consisted of a parametric test program using 29 configurations. These configurations were divided into three basic mixer options as shown in Figure 25. The short option provided for the lightest weight and was designed with very aggressive aerodynamic requirements to examine the impact of primary flow separation in the lobes. It was considered an extreme in the test matrix. The intermediate option, while not as aerodynamically aggressive as the short option, still provided for an aggressive weight reduction and decrease in overall length for the E³ mixer when compared to the more conservative aerodynamic approach of the long mixer. Figure 26 identifies the main test parameters investigated during this first test series. The variation in test parameters was accomplished by configuring the long, intermediate, and short options so as to cover the range of test parameters desired. The results of this test series was reported in Reference 17.

For the short mixer, the penalties associated with flow separation in the primary lobes were found to be significant. While the level of mixing was relatively good, the corresponding pressure loss was very high. Diagnostics indicated that the primary flow was indeed separated near the mixer exit as expected. The short mixer's main advantages of lightness and low external drag were more than offset by the large pressure losses observed. No further testing was conducted with this extremely short mixer option.

The intermediate option mixers were used mostly to examine mixing chamber length (L/D) and lobe number. The performance of these mixers did show benefits for a long mixing chamber and 18 lobe mixers. However, when the intermediate option mixer was tested initially with a short mixing chamber, it showed an unexplainably low level of performance.

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Since this was to be the basis against which most of these variables were to be reported, the effect of increased lobe number and mixing chamber length (L/D) are somewhat exaggerated, as described in Reference 17.

The long option mixers also examined lobe number, mixing chamber length, and the effect of scalloping. This series of tests provided data and trends as shown in Figure 27. The 18 lobe mixers showed a performance advantage of approximately 0.2 percent SFC over the twelve lobe configurations for both the conventional and scalloped mixer designs. Detailed analysis of the data indicated that the performance gains were due to increased mixing, even though the internal pressure losses did increase slightly. When a long mixing chamber length (L/D = 1.0) was installed on these mixers, the SFC improved 0.43 percent compared to a short mixing chamber length (L/D of 0.5) installed on the same mixer. This SFC improvement was due primarily to an increase in the level of mixing while the pressure loss increased only slightly. Scalloping is seen to further increase performance by approximately 0.35 percent SFC in both the twelve and eighteen lobe configurations. The performance gain associated with scalloping is a combination of reduced total pressure losses and increased mixing. While the effect of penetration was not systematically varied during the first series of tests, all three mixer options did have different levels of penetration (i.e., short mixer penetration 0.50, long mixer 0.57, and intermediate mixer 0.65). By selecting reasonable and consistent data points from tests of all three mixer designs, it was determined that the effect of penetration was substantial.

The second series of tests now planned will examine mixer overall length and flow turning rates in the lobes. The designs will take advantage of the benefits discovered for 18 lobes, increased mixing chamber length, and scalloping, while increasing penetration. Some small variations in plug gap will also be examined.

High Pressure Turbine Development - The PWA single-stage high-work, high-pressure turbine (HPT) FPS design employs transonic aerodynamics and single crystal airfoils. Originally, the design employed two-piece airfoils. This approach permits the use of complex internal cooling design, highly twisted

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and cambered airfoils (as shown in Figure 28), and thin tapered walls needed to meet the design goal requirements for life and aerodynamic performance. The long chord vanes and highly twisted blades are significantly larger than state-of-the-art single crystal vanes and blades. To experimentally substantiate the aerodynamic design for the HPT, an HPT Uncooled Rig Test Program was undertaken. This test program has been completed and is reported in Reference 18. The test program did substantiate the PWA design, demonstrating an uncooled efficiency level of 91.2 percent as compared to the goal efficiency level of 90.8 percent.

A Fabrication Development Program, investigating casting and subsequent bonding of the E³ two-piece airfoils approach was also conducted. The objectives of the casting portion of this program were to determine the feasibility and reproducibility of casting E³ size and geometry single crystal vanes and blades in halves, while maintaining internal and external dimensional control. The objectives of the bonding portion of this program were to evaluate the feasibility and reproducibility of bonding E³ size and geometry two-piece vane and blade halves while maintaining dimensional control and to provide verification of single crystal microstructure at the bond joint. A cast two-piece single crystal HPT blade is shown in Figure 29. The complex internal cooling geometry and high degree of blade twist can be seen from this figure. The feasibility of bonding two-piece vanes and blades was also demonstrated. A successfully bonded E³ two-piece HPT vane is shown in Figure 30. Some minor problems were encountered, however, with bonding the blade in the root section. These problems can be corrected by reducing the large mass in the lower part of the blade (shown in Figure 29), reducing the bond plane camber in this area, and possibly by local bond surface matching. Microstructure analysis of vane and blade sections at the bond joints showed that the single crystal material was retained. Figure 31 shows an example of a typical airfoil bond joint microstructure. Bonding reproducibility of the vane was demonstrated. Reproducibility of bonding the blade was inconsistent because of bond die - blade airfoil contour mismatch. It is expected that this can be corrected for the engine blades by improved contour fitup and controlled assembly. All major objectives of the casting and bonding programs were met. The feasibility of casting

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two-piece E³ size and geometry vanes and blades was demonstrated. The casting program provided the required parameters for fabricating the single crystal engine vanes and blades and demonstrated required crystal quality and dimensional reproducibility of the parts (airfoil halves).

The Fabrication Development Program provided for the HPT vane and blade design the required casting and bonding parameters necessary for successful fabrication of two-piece airfoils of the size and geometry unique to the E³ FPS design. Although it was originally thought that two-piece airfoil fabrication was required because of the complex internal cooling geometries and wall thickness requirements, recent industry experience now indicates that the vanes and blades can be cast in a single piece. Therefore, the PWA/E³ ICLS will use single crystal, one-piece, HPT vanes and blades. However, the technology demonstrated by the Fabrication Development Program will enable more complex turbine designs to be considered in the future.

CONCLUDING REMARKS

The E³ Project is structured to provide the advanced-technology base for a new generation of fuel-conservative engines that could be introduced into airline service by the late 1980's or early 1990's. E³ is directed at advancing engine component and systems technologies to the point of demonstration of technology-readiness by 1984. The flow of the technology to E³ applications is illustrated in Figure 32. Commercial development of new engines could be initiated by the engine manufacturers to meet potential airline needs of the 1990's. Selected technologies could be incorporated into derivative versions of current engines for introduction into airline fleets by the mid-to-late 1980's.

Both GE and PWA are heavily engaged in experimental efforts to develop the component technologies required in their respective E³ designs. Results of some of this effort has been reported in this paper and are considered promising. The outlook, therefore, continues to be optimistic that the performance advantage projected in the E³ goals can be achieved with the current designs.

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REFERENCES

1. D. L. Nored, et. al., "Aircraft Energy Efficiency (ACEE) Status Report". Aeropropulsion 1979, NASA Conference Publication 2092, October 1979.
2. R. G. O'Lone, "Fuel Shortage Causing Concern". Aviation Week and Space Technology, March 3, 1980.
3. N. T. Saunders, R. S. Colladay, and L. E. Macioce, "Design Approaches to More Energy Efficient Engines". AIAA Paper 78-931 (also NASA TM-78894), July 1978.
4. R. F. Patt, "Energy Efficient Engine Flight Propulsion System - Aircraft/Engine Integration Evaluation", NASA CR-159584, General Electric Company, June 1980.
5. R. E. Owens, "Energy Efficient Engine - Propulsion System - Aircraft Integration Evaluation", NASA CR-159488, Pratt & Whitney Aircraft Group, March 1979.
6. N. T. Saunders, "Advanced Component Technologies for Energy-Efficient Turbofan Engines". NASA TM-81507, June 1980.
7. R. P. Johnston, et. al., "Energy Efficient Engine - Flight Propulsion System Preliminary Analysis and Design Report". NASA CR-159583, General Electric Company, May 1980.
8. W. B. Gardner, et. al., "Energy Efficient Engine - Flight Propulsion System Preliminary Analysis and Design Report". NASA CR-159487, Pratt & Whitney Aircraft Group, April 1979.
9. R. P. Johnston, and P. Ortiz, "Future Trends in Subsonic Transport Energy Efficient Turbofan Engines", ASME Paper 80-GT-177, March 1980.
10. W. B. Gardner and D. E. Gray, "The Energy Efficient Engine (E³) -- Advancing the State of the Art", ASME Paper 80-GT-142, March 1980.
11. C. C. Gleason, and D. W. Bahr, "The Experimental Clean Combustor Program - Phase III Final Report", NASA CR-135384, June 1979.
12. D. L. Burrus, P. E. Sabla, D. W. Bahr, "Quiet Clean Short Haul Experimental Engine (QCSEE) Double Annular Clean Combustor Technology Development Report", NASA CR-159483, May 1979.
13. "Control of Air Pollution From Aircraft and Aircraft Engines - Proposed Amendments to Standards", EPA, Federal Register, Volume 43, Number 58, March 1978.
14. C. C. Gleason, D. W. Rogers, and D. W. Bahr, "Experimental Clean Combustor Program Phase II - Final Report", NASA CR-134971, August 1976.

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15. A. P. Kuchar, General Electric Company, and R. Chamberlin, NASA Lewis, "Scale Model Performance Test Investigation of Exhaust System Mixers for an Energy Efficient Engine (E³) Propulsion System" AIAA Paper 80-0229. Presented at AIAA 18th Aerospace Sciences Meeting, January 1980.
16. W. B. Wagner and S. Tanrikut, Pratt & Whitney Aircraft Group, and D. E. Sokolowski, NASA-Lewis, "Performance of Annular Prediffuser-Combustor Systems", ASME Paper 80-GT-15 presented at the Gas Turbine Conference, New Orleans, Louisiana, March 1980.
17. H. Kozlowski, Pratt & Whitney Aircraft, and G. Kraft, NASA-Lewis, "Experimental Evaluation of Exhaust Mixers for an Energy Efficient Engine". Paper AIAA-80-1088 presented at the 16th AIAA/SAE Joint Propulsion Conference, Hartford, Connecticut, June 1980.
18. D. E. Crow, Pratt & Whitney Aircraft, M. R. Vanco, NASA-Lewis, H. Welna and I. D. Singer, Pratt & Whitney Aircraft, "Results from Tests on a High Work Transonic Turbine for an Energy Efficient Engine." ASME Paper 80-GT-146, March 1980.

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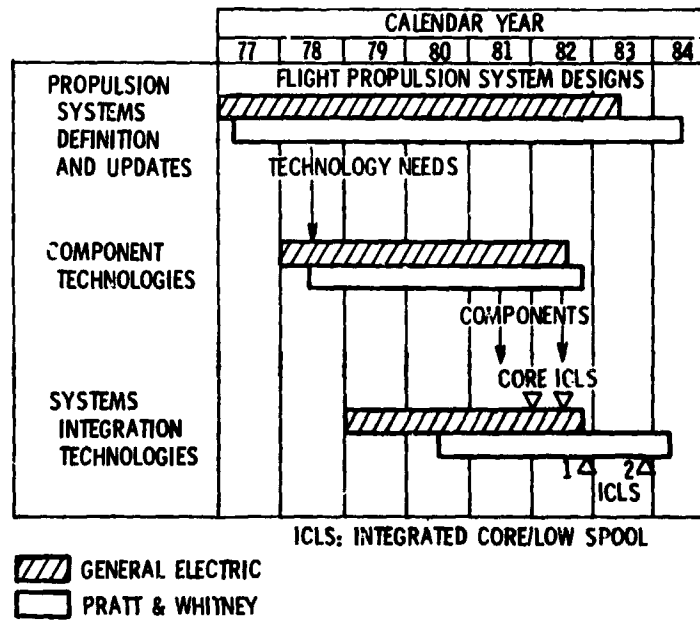


Figure 1. - Summary schedule of Energy Efficient Engine (E³) Project.

	PRATT & WHITNEY		GENERAL ELECTRIC	
	JT9D-7A	EEE	EEE	CF6-50C
FAN DRIVE	DIRECT	DIRECT	DIRECT	DIRECT
EXHAUST CONFIGURATION	SEPARATE	MIXED	MIXED	SEPARATE
BYPASS RATIO	5.1	6.61	6.9	4.3
FAN PRESSURE RATIO	1.58	1.71	1.61	1.73
COMPRESSOR PRESSURE RATIO	10	14	22.6	12.5
OVERALL PRESSURE RATIO	25.4	37.3	36.1	30.1
TURBINE TEMPERATURE, K (°F)				
MAX. CRUISE	1360 (1990)	1470 (2190)	1460 (2170)	1410 (2080)
HOT-DAY TAKEOFF	1520 (2285)	1635 (2480)	1620 (2450)	1590 (2400)

Figure 2. - Cycles selected for E³ designs (Max. cruise conditions).

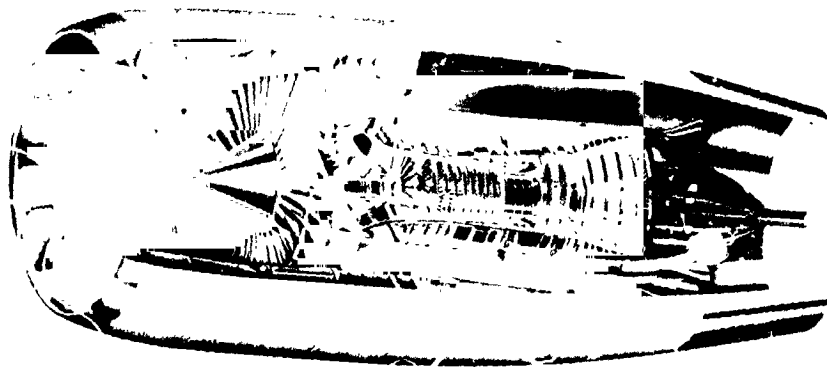


Figure 3. - General Electric E³ Configuration.

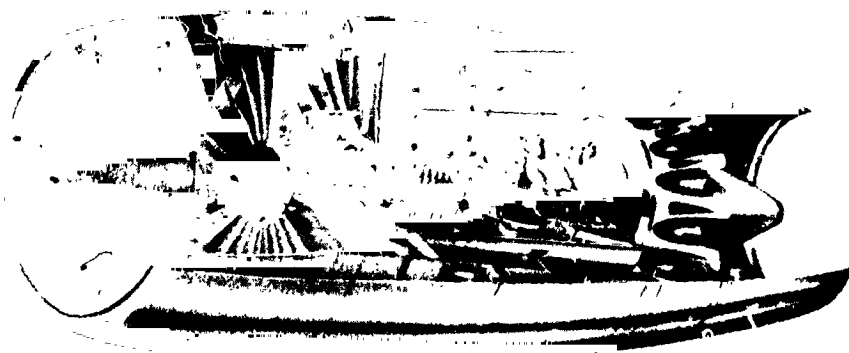


Figure 4. - Pratt and Whitney E³ Configuration.

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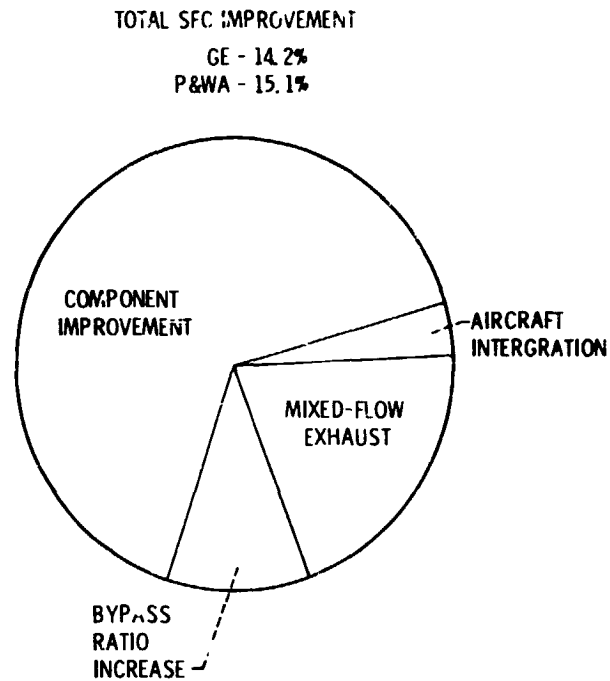


Figure 5. - Contributions to SFC improvement relative to CF6-50C/JT9D-7A.

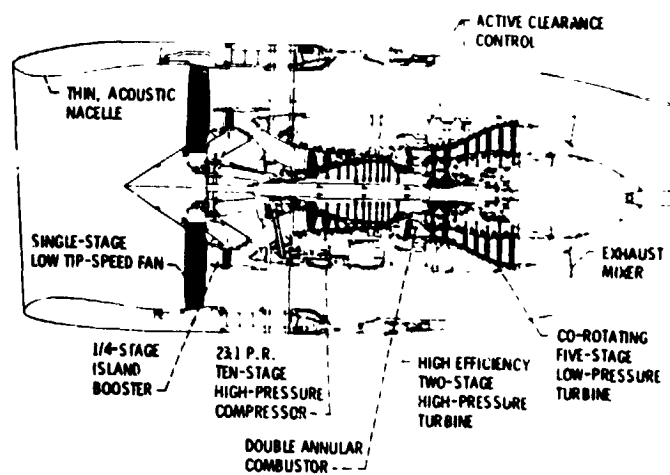


Figure 6. - Energy Efficiency Engine configuration (General Electric).

	<u>GOAL</u>	<u>FPS PROJECTION</u>
SFC	-12.0%	-14.2%
DOC	-5%	-5 TO -12%
PERFORMANCE RETENTION	50%	50%
NOISE	FAR36 (1978)	MEETS GOAL WITH AT LEAST 3 EPNdB MARGIN
EMISSIONS	EPA NEW ENGINE JAN. 1981 STANDARD	MEETS THE GOAL

Figure 7. - Projected performance status of GE/E³ Flight Propulsion System (FPS) relative to CF6-50C.

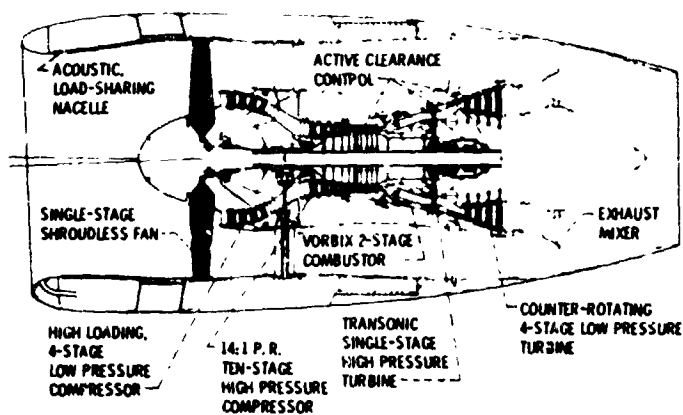


Figure 8. - Energy Efficient Engine configuration (Pratt & Whitney).

	<u>GOAL</u>	<u>FPS PROJECTION</u>
SFC	-12.0%	-15.1%
DOC	-5%	-5 TO -10%
PERFORMANCE RETENTION	50%	50%
NOISE	FAR36 (1978)	MEETS GOAL WITH 2 EPNdB MARGIN
EMISSIONS	EPA NEW ENGINE JAN. 1981 STANDARD	MEETS ALL BUT NO _x

Figure 9. - Projected performance status of PWA/E³ Flight Propulsion System (FPS) relative to JT9D-7A.

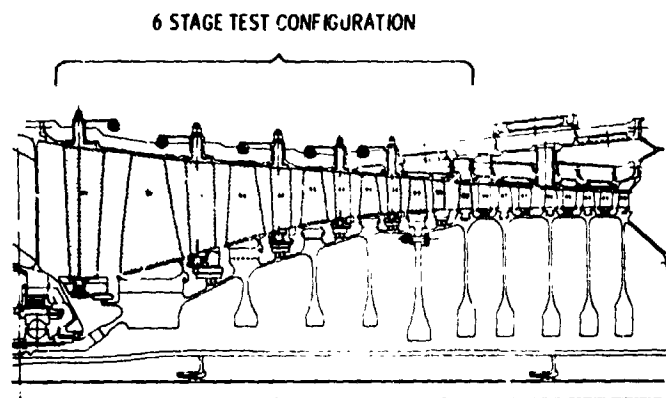


Figure 10. - GE/E³ - High pressure compressor.



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Figure 11. - GE/E³ - 1-6 high-pressure compressor rotor assembly.

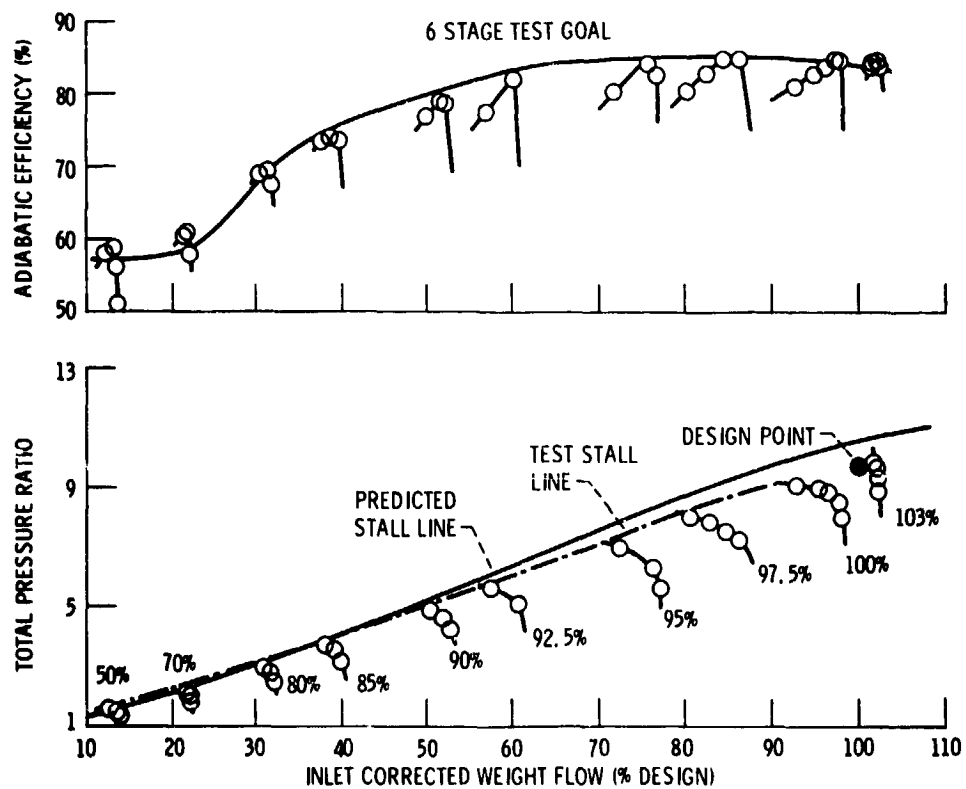


Figure 12. - GE/E³ - 1-6 High-pressure compressor test performance.

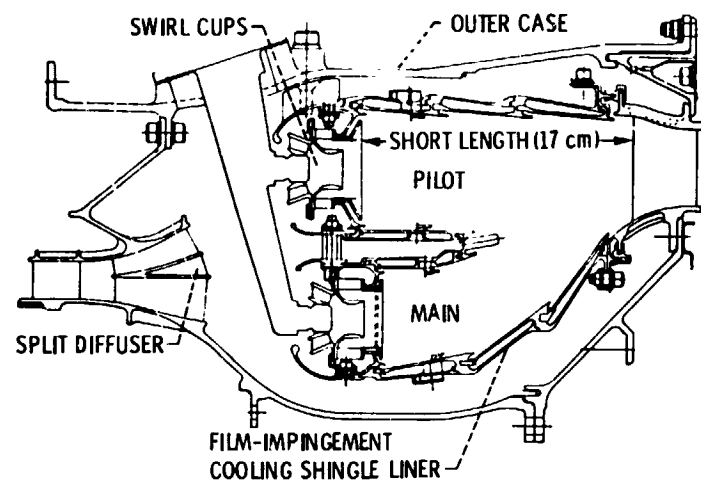


Figure 13. - GE/E³ combustor configuration.

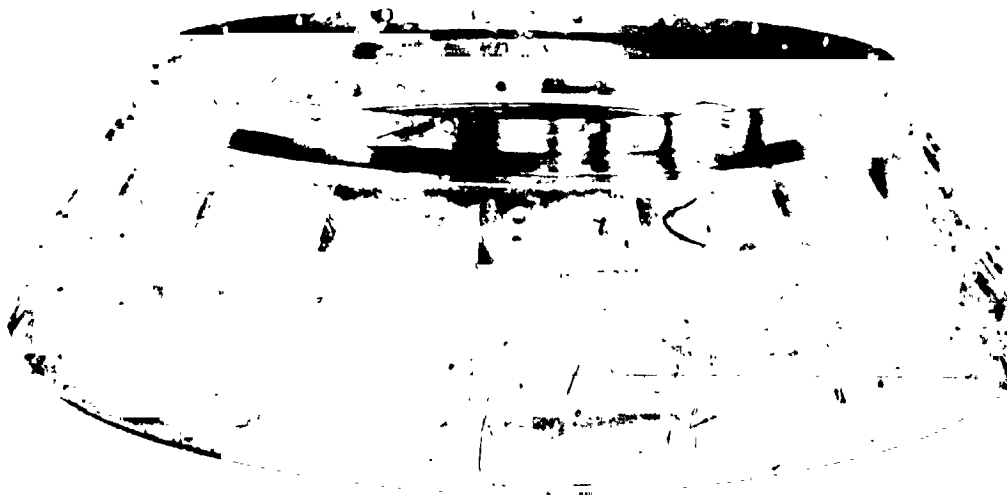


Figure 14. - GE/E³ - typical shingle combustor inner liner assembly.

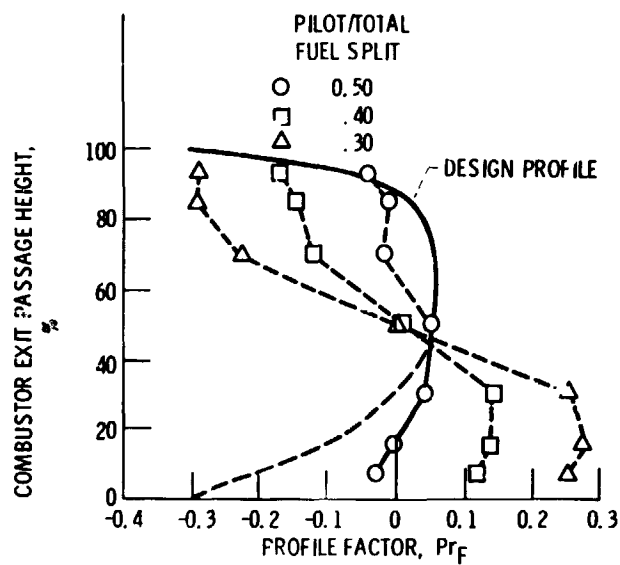


Figure 15. - GE³ combustor exit plane profile factor (SLTO, $\bar{t}/a = 0.024$).

PARAMETERS

- LOBE NUMBER (12, 18, 24)
- PERIMETER (P)
- LOBE SHAPE (2 CONFIGURATIONS)
- GAP HEIGHT (G)
- MIXING CHAMBER LENGTH (L/D)
- LOBE PENETRATION (A_{pen}/A_{mix})
- SCALLOPING (1 CONFIGURATION)

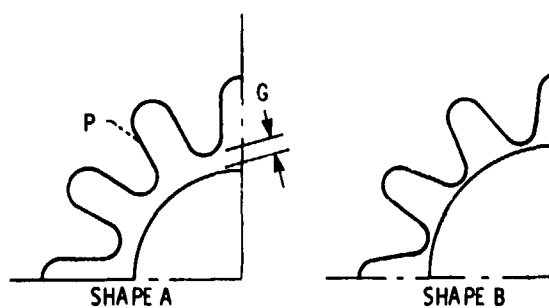
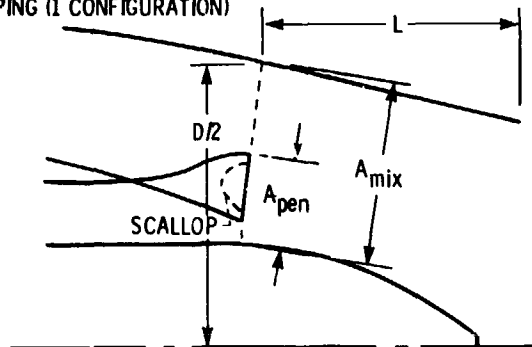


Figure 16. - GE/E³ - Mixer geometric test variables.

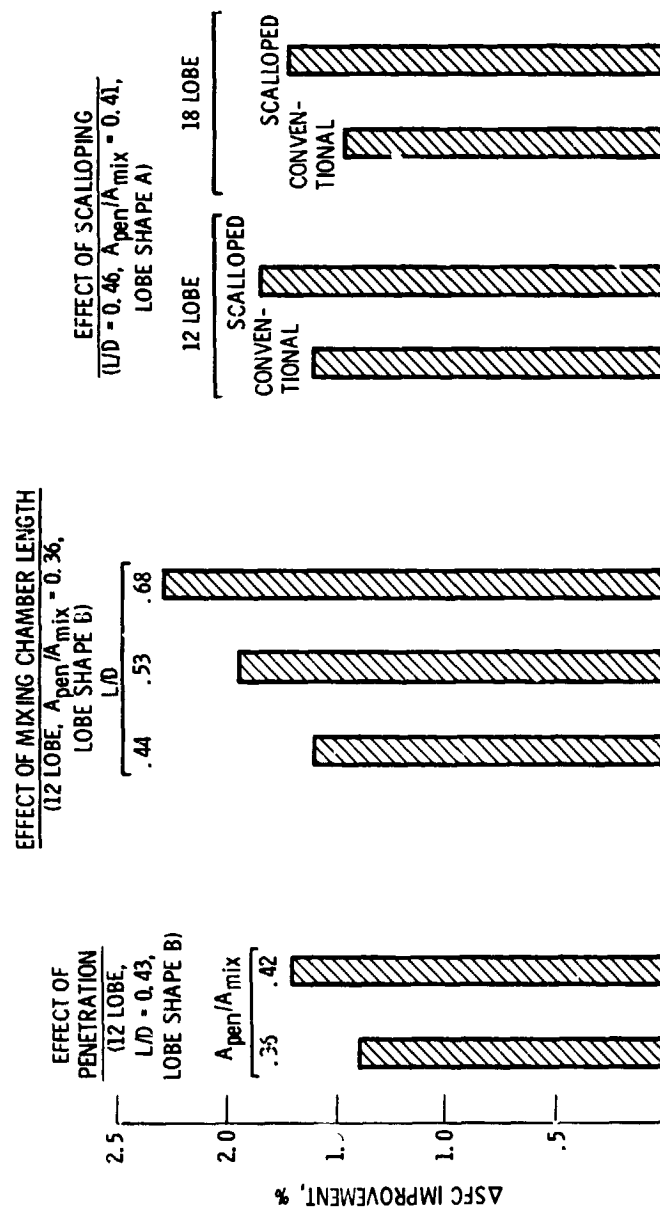


Figure 17. - GE/E^3 - Significant trends from mixer model tests.

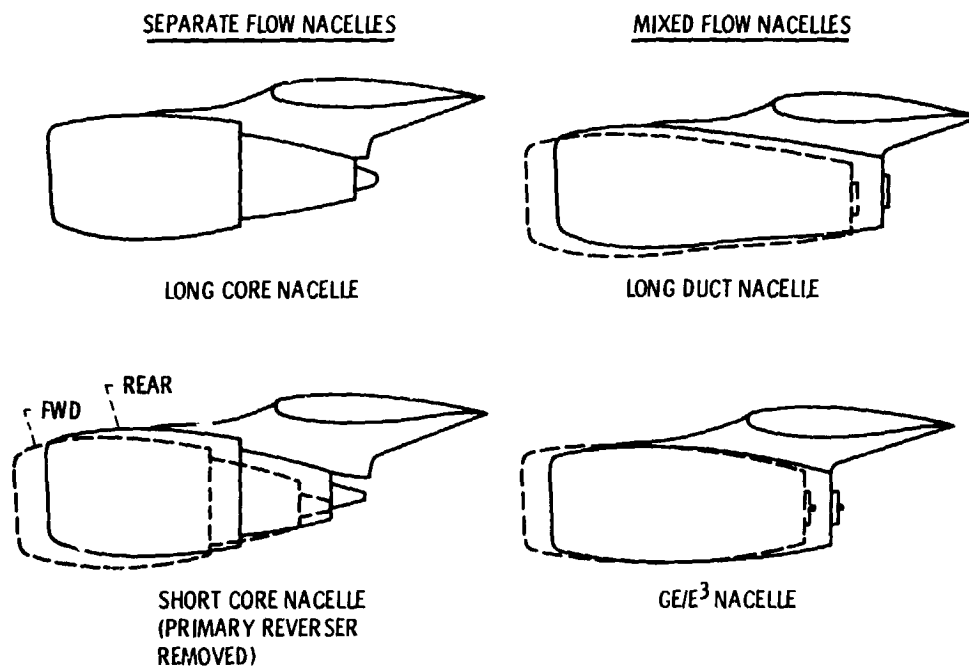


Figure 18. - GE/E³-Installed Nacelle configurations tested at Langley on EET model.

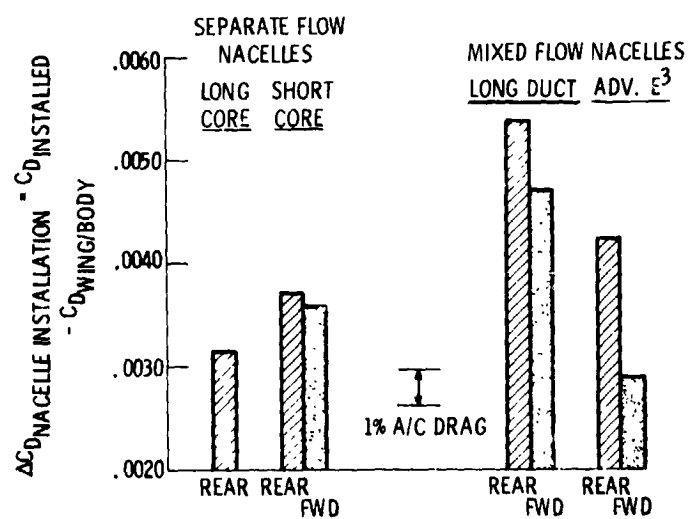


Figure 19. - GE/E³ - Installed nacelle drag (Mach 0.82, C_L 55).

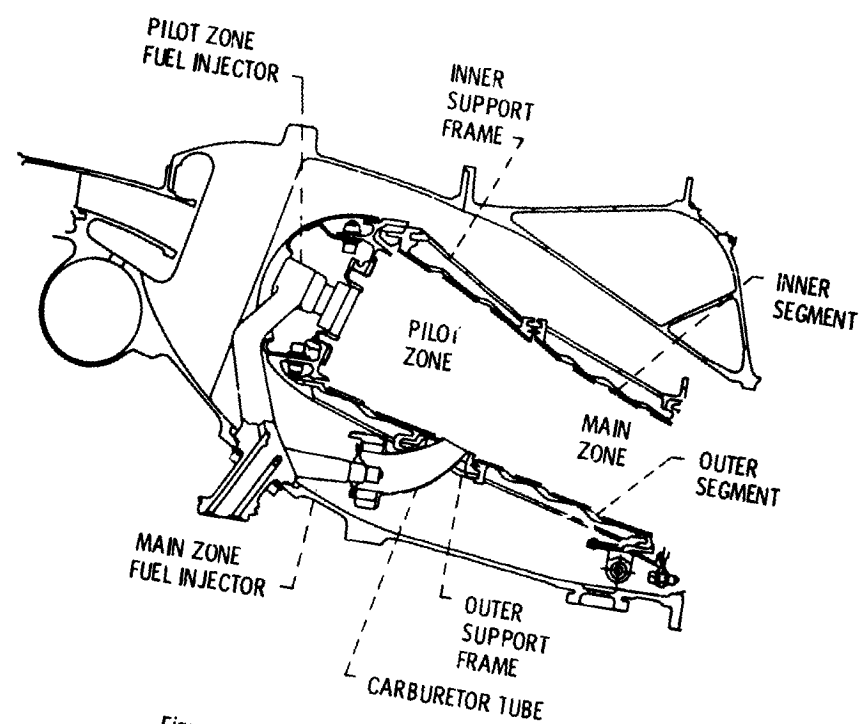


Figure 20. - PWA/E³ - Combustor configuration.

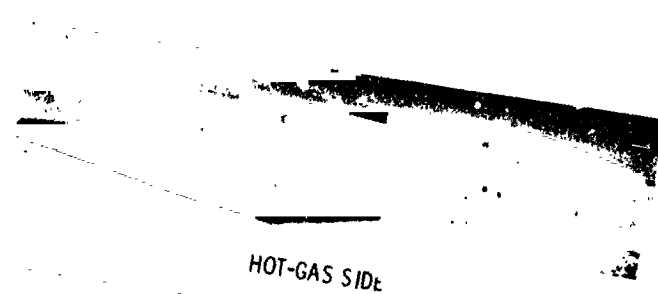


Figure 21. - PWA/E³ advanced combustor inner segment.



Figure 22. - PWA/E³-90° sector combustor installed in test rig.

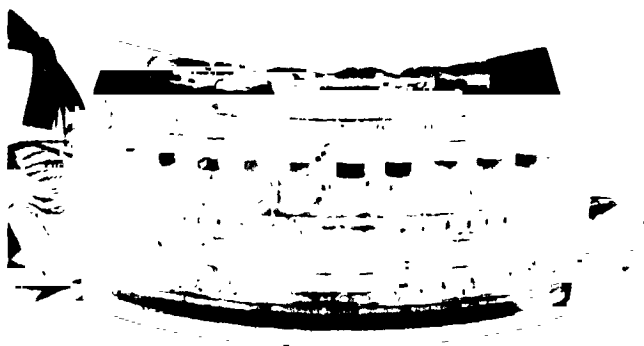


Figure 23. - PWA/E³-90° sector combustor showing outer liner and carburetor tubes.

- 12-OF-21 TESTS COMPLETED $P_{T3} = 16$ atmospheres
 $T_{T4} = 1560^{\circ} \text{ K (2345}^{\circ} \text{ F)}$
 - SUCCESSFUL TWO-ZONE OPERATION USING CARBURETOR TUBES
 - PILOT ZONE DEVELOPMENT COMPLETED
- | | STATUS | GOAL |
|-----------------------------------|--------|-----------------|
| ● EMISSIONS: NO_x (EPAP) | 4.65 | (≤ 3.0) |
| CO (EPAP) | 2.07 | (≤ 3.0) |
| HC (EPAP) | 0.26 | (≤ 0.4) |
| SMOKE (SAE NO.) | 1 | (≤ 20) |
| ● PATTERN FACTOR: | 0.15 | (≤ 0.37) |
| ● OVERALL PRESSURE LOSS (%) | 5.37 | (≤ 5.5) |
- ALTITUDE RE-LIGHT TESTING COMPLETED SUCCESSFULLY

Figure 24. - PWA/E³ - Status of test results from 90° sector combustor.

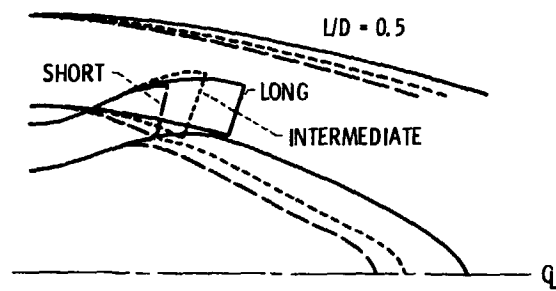
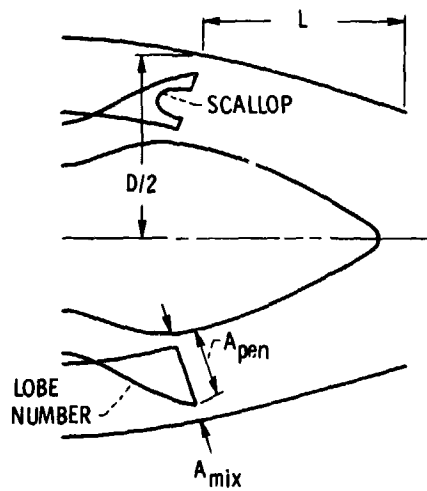


Figure 25. - PWA/E³ mixer options.



- LOBE PENETRATION, A_{pen}/A_{mix} (0.5, 0.57, 0.65)
- MIXING CHAMBER LENGTH, L/D (0.5, 1.0)
- LOBE NUMBER (12, 18)
- WITH AND WITHOUT SCALLOPS

Figure 26. - PWA/E³ test parameters.

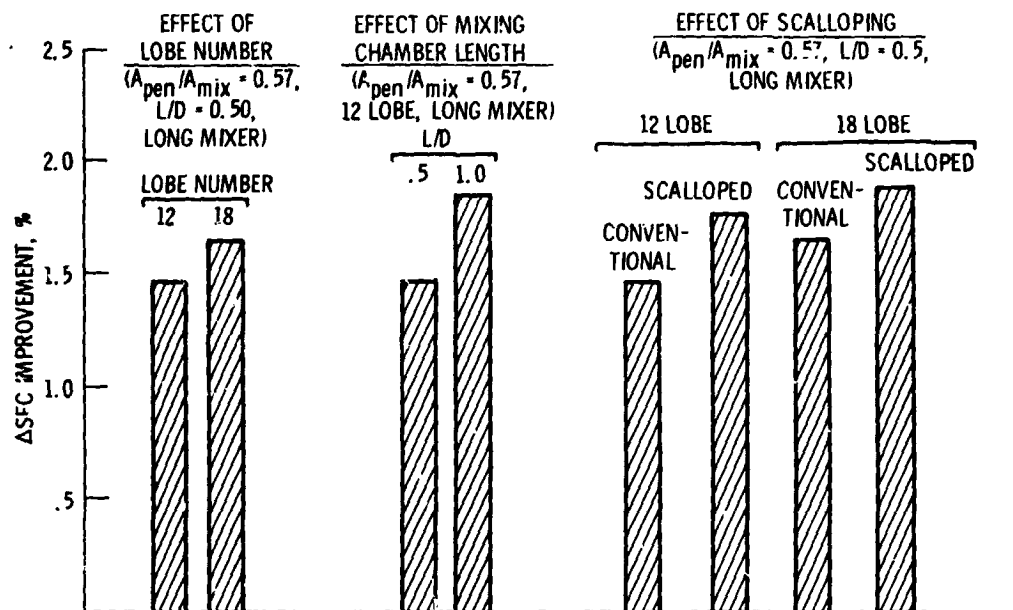


Figure 27. - PWA/E³ - Significant trends from first series model tests.

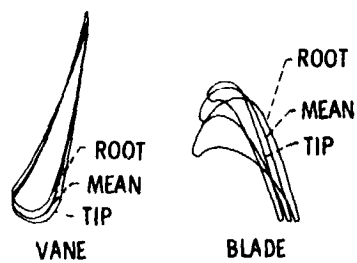


Figure 28. - PWA/E³ HPT blade and vane cross sections.

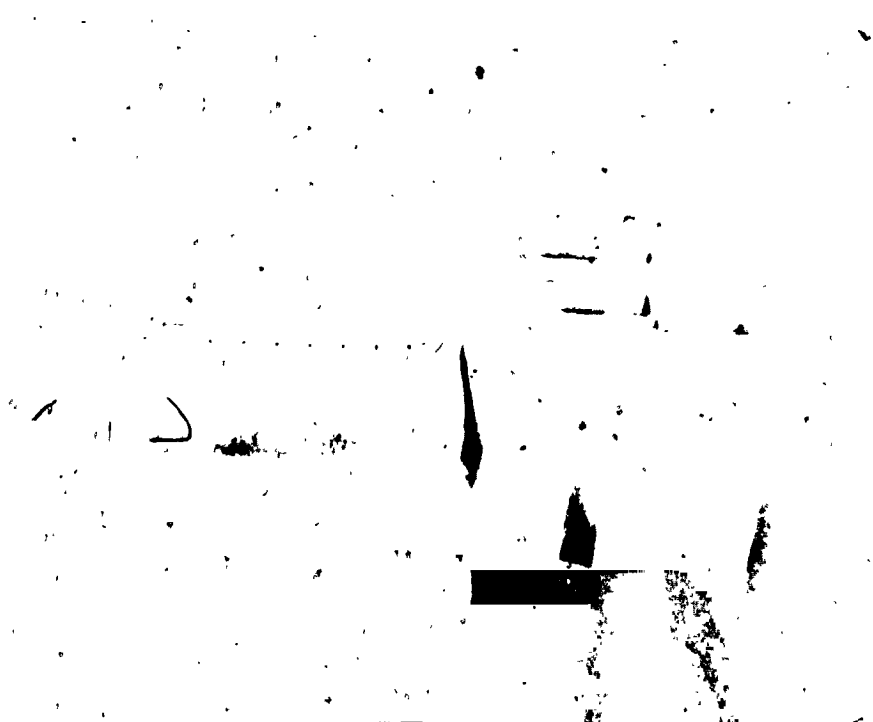


Figure 29. - PWA/E³ cast 2-piece single crystal HPT blade prior to bonding.



Figure 30. - PWA/E³ successfully bonded E³ 2-piece single crystal HPT vane.

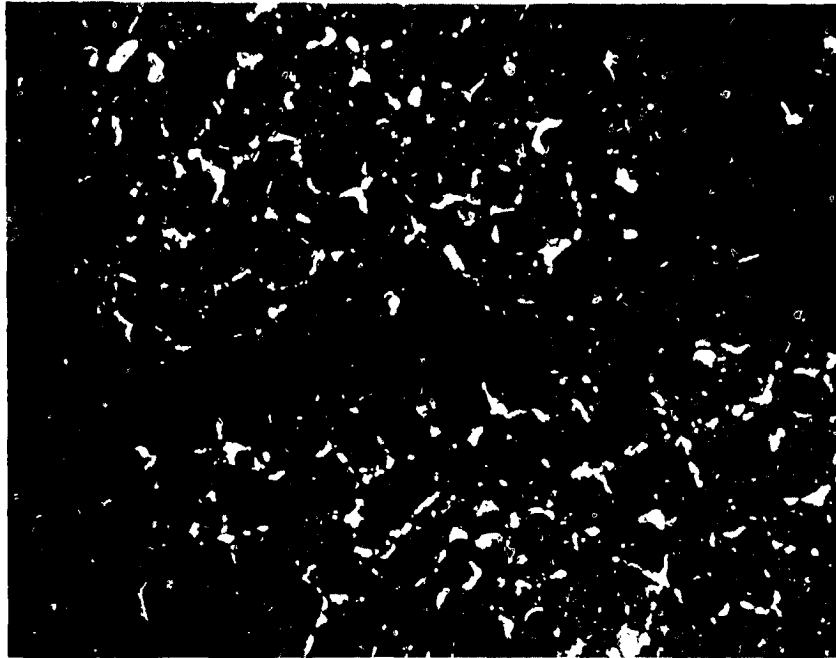


Figure 31. - PWA/E³ - typical HPT airfoil bond microstructure.

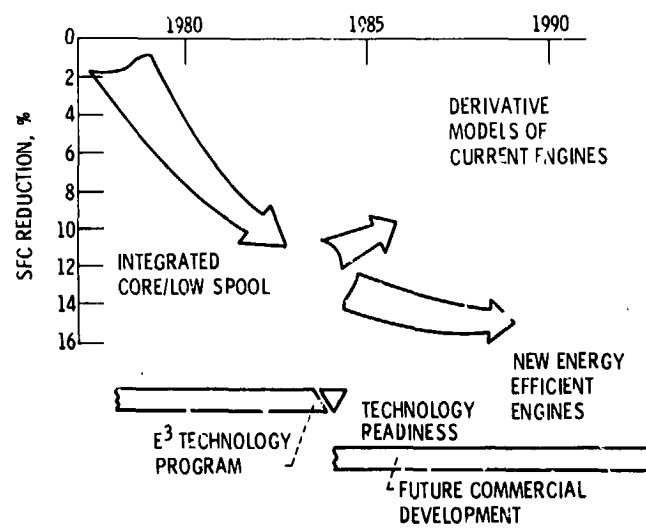


Figure 32. - Introduction of E³ Technology.